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AUTHOR(S): J. Douglas Balcomb

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HEAT STORAGE DURATION*

J. Douglas Balcomb
Los Alamos National Laboratory
Los Alamos, New Mexico 87545

ABSTRACT

Both the amount and duration of heat storage in massive elements of a passive building are investigated. Data taken for one full winter in the Balcomb solar home are analyzed with the aid of sub-system simulation models. Heat storage duration is tallied into one-day intervals. Heat storage location is discussed and related to overall energy flows. The results are interpreted and conclusions drawn.

1. INTRODUCTION

Heat storage is an essential characteristic of any passive solar building if heating loads other than those coincident with solar radiation are to be satisfied. Most passive solar designs seek to achieve solar savings of 50 percent or more and this requires significant storage of daytime solar gains to meet nighttime and cloudy-day loads. Yet despite the key importance of heat storage to passive solar performance there has been relatively little study of how long heat is stored in a passive solar building. The normal methods of interpreting results of simulation analysis tend to mask a good understanding of just when heat is stored and for how long.

In order to investigate the heat storage duration in a passive building, it was felt that it would be preferable to use data from an actual building rather than rely on a total system simulation. In this case the actual room temperatures are known and the simulation consists only of sub-system analysis reflecting the heat storage interactions within the various masses of the building. This removes any error which may be associated with predicting the temperatures within the spaces and brings the problem much closer to reality since it is an actual situation which is being analyzed rather than a hypothetical one.

The building which has been analyzed is the Balcomb solar home located in Santa Fe, New Mexico. The building has been well instrumented and evaluated and its operating characteristics are reasonably well known.[1,2]

2. OVERALL ENERGY PERFORMANCE

The data period which has previously been studied is the same as the one analyzed in this paper. It encompasses 176 days of winter from November 1, 1978 through April 24, 1979.

The overall energy balance numbers for this six-month period are given in Table 1. These are repeated here from the more detailed table given in Ref. 1 in order to provide a benchmark against which to measure the heat storage energies. The "useful load" is a number of particular interest. It is computed by subtracting from the total heat losses all vented energy and all energy required to maintain the house above 70 F and the greenhouse above 45 F.

Table 1
HEATING SEASON SUMMARY
(units are million Btu)

Solar Gains		96.2
Heat Losses (excl. vented)		112.4
House	66.5	
Greenhouse	35.8	
Evaporation	10.1	
Useful Load		89.3
House	66.0	
Greenhouse	23.3	
Vented		13.4
Auxiliaries		7.5
Internal Gains		22.1
Heating Required		67.2
Solar Savings		59.7

* Work performed under the auspices of the US Department of Energy, Office of Solar Applications for Buildings.

3. HEAT STORAGE MODELS

Heat storage has been calculated for 12 different discrete locations within the house in order to account for nearly all of the mass which may be effective. The procedure employed is to use hourly data to drive hour-by-hour simulation models characterizing the various heat storage elements. These models were previously validated by comparison of calculated mass storage temperatures with data taken during a six-week evaluation period when 85 channels were recorded. This combined approach allows an evaluation of when heat is put into a given storage element and when it is withdrawn.

Very simple thermal network models were developed for two different elements in each of three different spaces within the house. In each case the network consists of one thermal resistance and one thermal capacitance. One element was used to represent the combination of wood-beamed ceiling, second-story wood floors, and furnishings within the spaces, and the second element was used to represent the plaster walls. For the entire 1950 sq ft of living space these elements have a combined total heat storage capacity of 27056 Btu/F.

Temperatures measured in the plaster walls and in the wood-beamed ceiling show a very good correspondence with the model predictions during the selected test period. The models are driven by the measured air temperature in the three different rooms. These temperatures represent three types of spaces in the house which have significantly different temperature profiles. They are the downstairs dining room (representing all of the downstairs which is convectively well coupled), the master bedroom (representing the east and west end rooms upstairs which is well coupled to the greenhouse wall), and the upstairs center bedroom (which is relatively isolated and heated primarily by convection from the greenhouse). See Ref. 1 for floor plans and a section through the house.

The adobe wall which separates the house from the greenhouse was represented by a ladder of six resistance-capacitance connections driven by the measured temperatures near the wall surfaces. Since three different rakes of thermocouples were placed through the wall this calculation was repeated three times for the 10-inch east and west walls downstairs and for the 14-inch upstairs wall. These represent the sunlit portions of the adobe wall separating the greenhouse from the house. Separate calculations were made for a curved section of adobe wall which encases a circular staircase at the intersection of the east and west walls. Since this wall sees little sun, the model was driven from air temperatures measured in the house and the greenhouse. The upper and lower sections were calculated separately since the boundary conditions are quite different. The total heat capacity of the adobe wall is 8813 Btu/F for the sunlit portions and 7632 Btu/F for the curved portion.

Heat storage in the 350 sq ft greenhouse floor was modeled using a six element resistance-capacitance ladder representing the top 30 inches of soil. The model has been validated by comparison with temperatures made at 2-inch, 6-inch, and 1-foot depths.

In the cases of both the adobe wall and sunspace floor the thermal diffusivity of the material was calculated based on intermediate temperature measurements as described in Ref. 3. The corresponding value of thermal conductivity is 0.34 Btu/F-ft-hr for the adobe wall and 0.7 for the greenhouse floor.

The rock bed model used is very complex and will not be described in detail here. It consists of two coupled thermal networks, one 15-node network representing the rock bed itself and another 29-node network representing the earth under the rock bed extending under the foundation walls to the ground outside. These models gave good correspondence with measured floor temperatures and temperatures in the rock bed. The heat capacity of the rock bed is 14224 Btu/F counting in the overlaying 7" floor slab.

4. HEAT STORAGE ACCOUNTING

On a typical day heat flows into a heat storage element during the day and back out at night. These heat flows were integrated on an hour-by-hour basis separately summing the heat flow into storage and out of storage. By analogy with accounting these were called "deposits" and "withdrawals." For each day the deposit was simply the integral of the positive heat flow into storage. The withdrawal started at the end of the deposit period and continued until the beginning of the next day's deposit period or until noon, whichever is earliest. Thus, a withdrawal can be definitely related to a prior deposit.

In accounting for heat storage duration the principle of "last in-first out" was used. A special computer code (called "BANKER") was written to keep track of which day's deposit the withdrawals would be drawn against. An example of this accounting is shown in Table 2. In this table the history is only kept back for six days, however, in the actual calculations a thirty-day record was kept. In this way one can see on days when there is a deficit (withdrawals greater than deposits) how many days prior the deposit was made against which the withdrawal is drawn.

Tallies like Table 2 were made for the entire year. The total heat stored for different durations were calculated by summing the columns in the tables.

5. RESULTS

The overall results of the analysis are given in Table 3 and Table 4. Table 3 shows the sum of all of the deposits and withdrawals from all of the heat-storing elements throughout the 176-day analysis period. This is broken down by five major categories showing that the adobe wall separating the house from the greenhouse is the predominant heat-storing element followed by the various other heat-storing aspects of the house itself, the greenhouse floor, and then the rock bed.

Table 3
HEAT STORED DURING THE 1978-79
HEATING SEASON
(units are million Btu)

	Deposits	Withdrawals	Lost
House*	14.8	14.8	
Sunlit Adobe Walls	12.2	12.2	
Shaded Adobe Walls	5.7	5.7	
Greenhouse Floor	6.6	5.4	1.2
Rock bed	5.0	2.6	2.4
Total	44.3	40.7	3.6

*excluding the adobe wall

Table 4 shows the duration of storage for the 40.7 million Btu of withdrawals. This is divided into diurnal storage, which is energy stored for less than 12 hours and then into one-day time periods as shown. The average time that heat is stored is 22 hours. Diurnal heat storage dominates the picture, accounting for more than 82% of all heat storage. Only 7.2 million Btu of heat is stored for more than 12 hours and the average time duration of this heat storage is 4.1 days.

Table 2 - EXAMPLE OF DEPOSIT-WITHDRAWAL HISTORY
House Plaster Walls, Roofs, and Furnishing (units are kBtu)

Date	Deposit	Withdrawal	Withdrawn against deposit made N days earlier* N=0	1	2	3	4	5	6	7 or more
Nov. 28	67	25	25							
Nov. 29	62	51	51							
Nov. 30	63	40	40							
Dec. 1	97	04	84							
Dec. 2	40	98	40	13	23	11	11			
Dec. 3	18	62	18					31		13
Dec. 4	149	83	83							
Dec. 5	104	94	94							
Dec. 6	43	110	43	10	57					
Dec. 7	24	68	24			9				35
Dec. 8	41	66	41							25
Dec. 9	88	50	50							
Dec. 10	141	80	80							
Dec. 11	113	52	52							
Dec. 12	106	75	75							
Dec. 13	65	90	65	25						
Dec. 14	90	71	71							
Dec. 15	131	100	100							
Dec. 16	103	154	103	31	19		1			
Dec. 17	50	80	50					5	25	

*N = 0 refers to diurnal storage (within 12 hours), N = 1 refers to 12-36 hours, N = 2 refers to 36-60 hours, etc.

Table 4
HEAT STORAGE DURATION (million Btu)

TOTAL WITHDRAWALS	40.70
Stored less than 12 hours	33.50
Stored 0.5 to 1.5 days	2.47
Stored 1.5 to 2.5 days	1.34
Stored 2.[illegible] [illegible] [illegible].5 days	0.90
Stored 3[illegible] [illegible] 4.5 days	0.53
Stored [illegible] to 5.5 days	0.46
Stored 5.5 to 6.5 days	0.47
Stored 6.5 to 7.5 days	0.11
Stored 7.5 to 8.5 days	0.07
Stored 8.5 to 9.5 days	0.02
Stored 9.5 to 10.5 days	0.18
Stored 10.5 to 11.5 days	0.03
Stored 11.5 to 12.5 days	0.16
Stored 12.5 to 13.5 days	0.01
Stored 13.5 to 14.5 days	0.04
Stored greater than 14.5 days	0.41

Of the 12.2 million Btu stored in the sunlit portions of the adobe walls, 10.3 million Btu is returned to the greenhouse and 1.9 million Btu flows through the wall into the house. This through-flow of heat arrives in the house primarily at night and primarily in the upstairs portions where the shading is less, the walls are thinner, and the room temperatures are slightly lower.

The character of heat storage in each of the various elements is reasonably similar except for the rock bed where the proportion of diurnal storage is only 56 percent of the total and for the house (walls, roof, furnishings, etc.) where the proportion of diurnal storage is 84 percent of the total.

6. INTERPRETATION

Nearly two-thirds of the useful load in the Balcomb solar home is satisfied by heat which is passively stored in various elements of the house. Heat stored in the rock bed by active fan-forced air flow plays a minor role in the overall energy balance.

By far the most important heat storage is diurnal, that is, heat which is withdrawn from storage within twelve hours after deposit. This represents over 4/5 of the total heat stored.

The non-diurnal withdrawals have a storage duration reasonably well spread over a period of about one week but drop off rapidly after that, as shown in Fig. 1. Since this longer term heat storage is comparable to the auxiliary heating in the house it is reasonable to assume that the auxiliary heating might nearly double in the absence of this longer term storage.

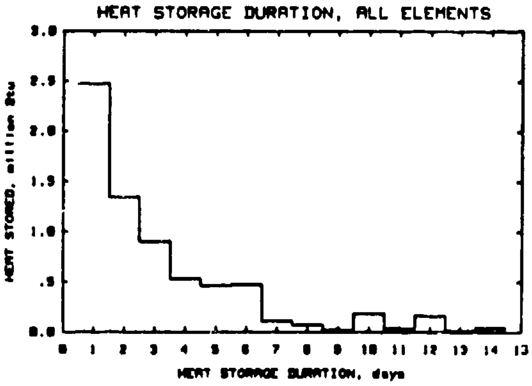

Fig. 1. Heat Storage Duration

Since there is no backup heating in the greenhouse, it is totally dependent at night on stored heat. This is obviously effective since the minimum temperature ever observed in the greenhouse is 43 F on a night when the outside temperature was -12 F and there had been no significant sunshine for three days. The predominant heat storage is in the adobe wall which separates the house from the greenhouse although the role of the greenhouse floor is also very important. The greenhouse never represents a significant load to the house.

The primary importance of the massive adobe wall between the house and the greenhouse is for direct-gain heat storage in the greenhouse. Most of the heat absorbed by the wall is released back to the greenhouse at night and is essential to maintaining reasonable temperature conditions in the greenhouse without backup heating. The "Trombe-wall effect" of this wall is also important, however, to supplying nighttime heating of the house, especially the upstairs.

The heat storage in the house itself (excluding the greenhouse wall) is very critical to the overall successful performance. The convective flow of heat through the doorways separating the greenhouse and house totals 16.9 million Btu for the year and the heat storage in the house is 14.8 million Btu. Although these cannot be related directly, because some of the stored heat is undoubtedly from internal gains, it is likely that a majority of the convected heat is stored. A secondary benefit of this storage is increased comfort by reducing temperature swings within the house (see Ref. 1 for temperature data).

The rock bed plays a fairly minor role in the overall energy balance of the house, accounting for only 7% of the stored heat which is returned to the house. The primary justification for the rock bed is seen in maintaining the floor temperatures in the living spaces about 10 F greater and thus improving the comfort characteristics of those spaces. Other advantages are in reducing the peak afternoon winter temperatures in the greenhouse by about 10 F and moving heat downward and northward in the building. The rock bed provides 16% of the house's longer-term storage.

In interpreting these results one must be aware that heat storage duration depends not only on both the design and operation of the building, but on the statistics of the weather. If the weather were identical each day, then long-term storage would be zero. Santa Fe, although cold, is relatively sunny with 62% of possible sunshine during this winter. There are long periods of sunny, crisp weather and the cloudy weather is dominated by cyclonic storms which cross the country dropping appreciable snowfall. The typical duration of these storm cycles is three days although they frequently overlap. This type of weather characterizes much of the US although the frequency and duration of cloudy weather is greater in many places.

It is informative to study the total heat storage capacity of each element evaluated in this analysis and compare that against the total withdrawals. This is shown in Table 5. Clearly the effectiveness of each element is not simply proportional to its storage capacity; the elements which are more accessible to direct solar heat and to solar heated air, by virtue of having a good location or a large surface area, are far more effective. The area of the greenhouse glazing is 409 sq ft; the second column in the table shows the amount of heat storage per unit of greenhouse glazing. Although the total heat storage is several times the minimum recommended value of 54 Btu/F-sq ft (for a 90% SSF building) much of this storage is remote and relatively ineffective.

Table 5
HEAT STORAGE COMPARED WITH HEAT CAPACITY

	Withdrawals (million Btu)	Heat capacity* (Btu/F-sq ft of glazing)
House	14.8	66.1
Sunlit Adobe Walls	12.2	21.5
Shaded Adobe Walls	5.7	18.7
Greenhouse Floor (to 30")	5.4	38.7
Rock bed (incl. floor)	2.6	34.8

*based on 409 sq ft of greenhouse glazing

7. CONCLUSIONS

Although the Balcomb house has a very high solar fraction (the solar savings represent 89% of the net heating requirement) it still seems that the predominant heat storage is diurnal. It is likely that one could design simply on the basis of providing sufficient diurnal storage and the longer term storage will follow automatically. However, the rock bed might be designed to more effectively take advantage of longer-term storage.

In calculating effective heat storage all of the mass in the building should be accounted. This is particularly true of large surface areas such as ceilings and furniture which are often ignored but which may have a substantial diurnal heat capacity. The ineffectiveness of mass which is remote, either because it is beneath overlaying layers or because it is in inaccessible rooms, can be accounted by performing diurnal heat capacity calculation (see Chapter F in Ref. 4).

The diversity of heat storage within the house is seen as an advantage.

8. ACKNOWLEDGEMENTS

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9. REFERENCES

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